FORECASTING AMERICANS' LONG-TERM ADOPTION OF CONNECTED AND AUTONOMOUS VEHICLE TECHNOLOGIES

Prateek Bansal
Graduate Research Assistant
Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin
prateekbansal@utexas.edu
Phone: 512-293-1802

Kara M. Kockelman
(Corresponding Author)
E.P. Schoch Professor in Engineering
Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin
kkockelm@mail.utexas.edu

Under review for publication in *Transportation Research Part A: Policy and Practice.*
(April 2016)

ABSTRACT

Automobile enterprises, researchers, and policymakers are interested in knowing the future of connected and autonomous vehicles (CAVs). To this end, this study proposes a new simulation-based framework to forecast Americans' long-term (year 2015 to 2045) adoption levels of CAV technologies under eight different scenarios based on: 5% and 10% annual drops in technology prices; 0%, 5%, and 10% annual increments in Americans' willingness to pay (WTP); and changes in government regulations. This simulation was calibrated with the data obtained from a survey of 2,167 Americans, in order to obtain their preferences for CAV technologies and their household's annual vehicle transaction decisions.

Results indicate that the average WTP (of respondents with a non-zero WTP) to add connectivity and Level 3 and Level 4 automations are $110, $5,551, and $14,589, respectively. Long-term fleet evolution suggests that the privately held light-duty vehicle fleet will have 24.8% Level 4 AV penetration by 2045 under an annual 5% price drop and constant WTP values. This share jumps to 87.2% under a 10% annual price drop and a 10% annual rise in WTP values. Additionally, in all scenarios with at least a10% annual increase in WTP or at least a 10% annual price reduction, all Level 1 technologies exceed 90% adoption rates by 2045. Overall, simulations suggest that, without a rise in people's WTP, or policies that promote technologies, or rapid reductions in technology costs, it is unlikely that the U.S. light-duty vehicle fleet's technology mix will be anywhere near homogeneous by the year 2045.

INTRODUCTION

There is much excitement about the future of car travel. Hybrid-electric vehicles, plug-in electric vehicles, carsharing services, and on-demand taxis are all examples of recent technological and strategic advances in the automobile and transportation sectors. However, the real vehicle-market revolution is associated with the introduction of autonomous vehicles (AVs), connected vehicles (CVs), and connected-autonomous vehicles (CAVs). CAVs introduce all sorts of different benefits from dramatic reduction of crash rates and congestion to concerns about security, safety and privacy, and negative economic consequences associated with transition to vehicle automation (Schoettle and Sivak 2014, Fagnant and Kockelman 2015, National Highway Traffic Safety Administration [NHTSA] 2013). Therefore, despite all the hype about CAVs, there is much uncertainty about the future of these technologies.

Forecasting long-term CAV technologies' adoption is not easy: many demand side (e.g., willingness to pay [WTP]) and supply side factors (e.g., technology prices) must be taken into account. Several researchers (Litman, 2015), private enterprises (e.g., Mosquet et al. 2015, Laslau et al. 2014), and industry enthusiasts (e.g., Rowe 2015, Hars 2014), have made different predictions about the CAV technologies' future adoption rates. However, these predictions are based on the extrapolation of trends associated with previous vehicle technologies, expert opinions, or forecasts of supply-side variables, with very little emphasis on the underlined assumptions behind these predictions. To the best of the authors' knowledge, demand-side considerations, like WTP for these technologies and vehicle transaction decisions, as well as government's regulations about mandatory technology adoption[1] are not taken into account in the previous studies. Moreover, none of these studies have mechanisms (except expert opinions) to anticipate the adoption of specific Level 1 and Level 2 automation technologies[2] (e.g., lane centering assistance and adaptive cruise control), and vehicle connectivity. This study aims to fill these gaps and proposes a simulation-based fleet evolution framework to forecast Americans' long-term (year 2015 to 2045) adoption of CAV technologies under eight-different scenarios based on: 5% and 10% annual drop in technology-prices; 0%, 5%, and 10% annual increment in Americans' WTP; and NHTSA's current and probable regulations on mandatory adoption of electronic stability control (ESC) and vehicle connectivity. These simulations predict the proportions of vehicles with specific technologies at the end of each year under these scenarios.

A survey was designed and disseminated to obtain 2,167 Americans' preferences (e.g., WTP for CAV technologies and vehicle transaction decisions), and those data were used in the simulation framework. To incorporate the impact of demographics and built-environment variables on vehicle transaction decision, logit models were developed; and those were also integrated in the proposed simulation framework. The following sections describe related studies, the survey and simulations design, summary statistics, modeling specifications, key findings, and conclusions.

LITERATURE REVIEW

Forecasting long-term adoption of CAV technologies is a fairly new topic. One of the most cited studies about CAV adoption is by Litman (2015). Based on deployment and adoption of previous smart vehicle technologies (like automatic transmission and hybrid-electric drive), Litman forecasted that AVs are expected to constitute around 50% of vehicle sales, 30% of vehicles, and 40% of all vehicle travel by 2040. He argues that faster implementation would require "low and

---

[1] ESC has been mandated on all new passenger vehicles in the US since 2012 model year (NHTSA 2012). NHTSA is expected to require connectivity on all vehicles produced after year 2020 (Automotive Digest 2014).

[2] NHTSA (2013) defined five levels of automation. To state briefly, automation Levels 0, Level 1, Level 2, Level 3, and Level 4 imply no automation, function-specific automation, combined function automation, limited self-driving automation, and full self-driving automation, respectively.

middle-income motorists, who normally purchase used vehicles or cheaper new models to spend significantly more in order to purchase a new automobile with self-driving capability."

Consulting firms, investments banks, and other private enterprises published several reports with predictions about CAVs technologies' expected market penetrations. A team from Lux Research (Laslau et al. 2014) predicts that the market size for Level 2 and Level 3 automation technologies will account for up to $87 billion by 2030. However, they argue that Level 4 technology is likely to be emerging by that time and Level 3 automation will still be a premium option, which is expected account for only 8% of new car sales.

Boston Consulting Group (Mosquet, et al. 2015) analysts predict that Level 4 AVs' sales will reach $39 billion or about 10% of all new light-vehicle sales by 2035. Researchers from Citi GPS (2014) believe that the market for fully-autonomous vehicles could reach $40 billion by 2025. IHS (2014) experts anticipate self-driving vehicles' sales to hit nearly 12 million by 2035 (around 9% of global auto sales) and full automation of entire vehicle-fleet by 2045.

A Navigant research study (Alexander and Gartner 2014) predicts autonomous vehicles' sales to reach around 18 million (or 75% of all light-duty vehicles) by 2035 in the U.S. IDTechEx (Harrop and Das, 2015) experts assess the number of self-driving capable cars to reach 8.5 million by 2035 in the U.S.

Experts and industry enthusiasts also presented their opinions on future driverless vehicle adoption rates. Rowe (2015) believes that Level 4 CAVs will be prohibited in the populous areas by 2025 to 2035. He mentions "by about 2060, manual control of cars anywhere near civilization will come to be seen kind of the way texting and driving is seen today: dangerous, stupid and sociopathic" and expects CAVs to be everywhere by 2050 to 2060.

On the very optimistic side of opinion spectrum, Hars (2014) believes that already by 2030, 90% of all trips will be happening in Level 4 AVs, and car ownership will decline to 20% in the U.S., due to projected popularity of SAVs. Alberto Broggi (Institute of Electrical and Electronics Engineers, 2012) is also very optimistic: he believes that up to 75% of all vehicles on the road will be autonomous by 2040.

Most of other recent studies (e.g., Schoettle and Sivak 2014 and Bansal et al. 2015) are focused on understanding respondents' currently perceived benefits and concerns about and present WTP for CAV technologies, among many other opinion-based attributes. To authors' best knowledge, this study is the first one to forecast long-term evolution of CAVs' fleet considering demand (consumers' WTP) and supply (technology prices) side variables, and NHTSA's regulations on ESC and vehicle connectivity. A few vehicle simulation frameworks have been developed for forecasting market shares of alternative fuel vehicles in Austin (Mushti and Kockelman 2010) and U.S. (Paul et al. 2011). However, these models are not directly applicable to forecasting the long-term adoption of CAV technologies, but provide a basis for this new framework.

SURVEY DESIGN AND DATA PROCESSING

A survey was designed and disseminated a U.S.-wide survey in June 2015 using Qualtrics, a web-based survey tool. The Survey Sampling International's (SSI, an internationally recognized and highly professional survey firm) continuous panel of respondents served as the respondents for this survey. Exploring respondents' preferences for the adoption of emerging vehicle and transport technologies, the survey asked respondents about their household's current vehicle inventory (e.g., odometer reading and average miles traveled per year), vehicles sold in the past 10 years, future vehicle preferences (e.g., buying or selling a vehicle), and WTP for various CAV technologies. Respondents were also asked for their opinions related to CAVs (e.g., comfort in allowing vehicle to transmit data to various agencies), travel patterns (e.g., using AVs for the long-distance trips), and demographics.

A total of 2,868 Americans completed the survey. Respondents who completed the survey in less than 13 minutes were assumed to have not read questions thoroughly, and their responses were discarded. Certain other respondents were considered ineligible for further analysis (e.g., those younger than 18 years and reporting more workers than household size). After removing the fast responses and conducting some sanity checks, 2,167 responses (1,364 Texans) remained eligible for further analysis. The sample over-represented Texans and specific demographic classes, such as female and bachelor degree holders, and under-represented others, such as men who did not complete high school and males 18 to 21 years old. Therefore, the survey sample proportions in 120 categories[3] (two gender-based, five age-based, six educational-attainment groups, and "respondent is Texan or not?") were scaled using the 2013 American Community Survey's Public Use Microdata Sample (PUMS 2013). These scale factors were used as person-level weights to un-bias person-related summary statistics (e.g., binary opinion whether AVs are realistic or not) and model-based parameter estimates.

Similarly, some household groups were under- or over-represented. Thus, household weights were calculated for 130 categories (4 household size groups, 4 household workers groups, 5 vehicle ownership groups, and "household is Texan or not?") using PUMS 2013 data. These household weights were used to un-bias household-related (e.g., WTP for new technologies and vehicle transaction decisions) model estimates and summary statistics.

To understand the spread of survey respondents across Texas and to account for the impact of built-environment factors (e.g., population density and population below poverty line) on household vehicle transaction and technology adoption decisions, the respondents' home addresses were geocoded using Google Maps API and spatially joined with U.S.'s census-tract-level shape file using open-source Quantum GIS. For respondents who did not provide their street address or recorded incorrect addresses, their internet protocol (IP) locations were used as the proxies for their home locations.

SUMMARY STATISTICS

Level 1 and Level 2 Technologies

Table 1 summarizes WTP for, interest in, and current adoption of CAV technologies. Among Level 1 and Level 2 automation technologies[4], the respondents showed the least interest in traffic sign recognition and left-turn assist technologies. Traffic sign recognition is of no interest to

[3] Out of 120 categories, 4 were missing in the sample, and were merged with adjacent categories.

[4] Level 1 and Level 2 automations are considered together and used interchangeably at a few places, since a combination of Level 1 technologies leads to Level 2 automation.

52.6% of the respondents, and 54.4% noted they are unwilling to pay anything to add this technology to their vehicles. Left-turn assist is slightly more acceptable: 46.9% of the respondents are not interested in it, and 46.1% would not to pay anything for it. Blind-spot monitoring is the most appealing technology for Americans and around half (50.7%) of the respondents are very interested, only 17.3% are not interested in it, and the smallest proportion of the respondents (only 23.7%) indicate $0 WTP for it. Emergency automatic braking is the second most interesting technology for Americans, with 45.8% of the very-interested respondents, 22.8% of the not-interested respondents, and only 28.7% of the respondents with $0 WTP.

Not surprisingly, among these Level 1 and Level 2 automation technologies, electronic stability control is the one most expected to be already present in the respondents' vehicles: 21.6% of those who have a vehicle reported having this technology in at least one household vehicle, and it is possible that many respondents are unaware that their vehicles now come equipped with such technology (since ESC has been mandated on all new passenger vehicles in the US since 2012 model year [NHTSA 2012]).

The respondents' WTP for Level 1 and Level 2 technology varies significantly[5]. The average WTP (among the respondents with non-zero WTP) to add ESC to an existing or a future vehicle exceeded the projected price after five years: $79 versus $70. For every other technology, the average WTP (of the respondents who are ready to pay for the technology) is lower than the estimated future price after five years. For example, average WTP to add emergency automatic braking is $257 (versus $320, the projected price after five years) and for blind-spot monitoring, it is $210 (versus $280). The worst ratio of the average WTP to the projected price is for the adaptive headlights: $345 versus $700. Respondents value this technology significantly; in fact, it is the second most valued technology in terms of average WTP (of the respondents who are ready to pay for the technology), but respondents probably believe that the projected price is still too high.

Table 1: Population-weighted Summaries for Level 1 and Level 2 Technologies (N_{obs}=2,167)

Electronic Stability Control			
WTP to Add		*Present in a Vehicle**	
Do not want to pay anything	33.4%	Yes	21.6%
Less than $60	16.8%	*Interested in Technology*	
$60 to $79	20.4%	Not interested	29.1%
$80 to $119	21.6%	Slightly interested	41.6%
$120 and more	7.8%	Very interested	29.3%
Average WTP to Add	$52	*Average WTP of those with WTP>0*	$79
Lane Centering			

5 Before asking a WTP question, respondents were provided with a price forecast for a particular technology. For example, the price forecast for ESC was "Current Price: $100; Price after 5 years: $70; Price after 10 years: $50". It is difficult to estimate the price of a particular Level 1 or Level 2 technology, since these technologies are provided in packages. For example, BMW provides a $1900 package with lane departure warning, forward collision braking, adaptive cruise control, pedestrian detection, and blind-spot monitoring. Thus, after analyzing different packages, current prices for each of these technologies were determined. Subsequently, 30% price reduction in the next 5 years and a 50% price reduction in the next 10 years were considered (with 7% annual price reduction rate) to provide future price estimates of these technologies.

WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	41.7%	Yes	3.9%
Less than $200	21.4%	*Interested in Technology*	
$200 to $399	14.2%	Not interested	37.8%
$400 to $599	12.4%	Slightly interested	39.0%
$600 and more	10.3%	Very interested	23.2%
Average WTP to Add	$205	*Average WTP of those with WTP>0*	$352
Left Turn Assist			
WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	46.1%	Yes	3.8%
Less than $100	14.9%	*Interested in Technology*	
$100 to $299	23.6%	Not interested	46.9%
$300 to $399	8.1%	Slightly interested	35.3%
$400 and more	7.3%	Very interested	17.8%
Average WTP to Add	$119	*Average WTP of those with WTP>0*	$221
Cross Traffic Sensor			
WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	32.8%	Yes	9.6%
Less than $100	15.2%	*Interested in Technology*	
$100 to $199	14.4%	Not interested	31.7%
$200 to $399	24.6%	Slightly interested	38.9%
$400 and more	13.0%	Very interested	29.3%
Average WTP to Add	$169	*Average WTP of those with WTP>0*	$252
Adaptive Headlights			
WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	41.1%	Yes	9.5%
Less than $150	17.7%	*Interested in Technology*	
$150 to $349	17.4%	Not interested	34.7%
$350 to $649	15.2%	Slightly interested	39.6%
$650 and more	8.7%	Very interested	25.6%
Average WTP to Add	$203	*Average WTP of those with WTP>0*	$345
Pedestrian Detection			
WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	37.5%	Yes	3.3%
Less than $100	16.0%	*Interested in Technology*	
$100 to $199	12.8%	Not interested	31.4%
$200 to $399	24.2%	Slightly interested	37.1%
$400 and more	9.5%	Very interested	31.5%
Average WTP to Add	$145	*Average WTP of those with WTP>0*	$232
Adaptive Cruise Control			
WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	37.7%	Yes	12.8%
Less than $150	26.2%	*Interested in Technology*	
$150 to $249	14.8%	Not interested	32.1%
$250 to $349	11.9%	Slightly interested	37.1%
$350 and more	9.4%	Very interested	30.8%
Average WTP to Add	$126	*Average WTP of those with WTP>0*	$202
Blind-spot Monitoring			
WTP to Add		*Present in a Vehicle*[*]	
Do not want to pay anything	23.7%	Yes	9.9%

Less than $150	29.5%	*Interested in Technology*	
$150 to $249	18.2%	Not interested	17.3%
$250 to $349	14.7%	Slightly interested	31.9%
$350 and more	13.9%	Very interested	50.7%
Average WTP to Add	$160	*Average WTP of those with WTP>0*	$210
Traffic Sign Recognition			
WTP to Add		*Present in a Vehicle**	
Do not want to pay anything	54.4%	Yes	2.1%
Less than $100	15.0%	*Interested in Technology*	
$100 to $199	9.6%	Not interested	52.6%
$200 to $299	10.1%	Slightly interested	30.1%
$300 and more	10.9%	Very interested	17.3%
Average WTP to Add	$93	*Average WTP of those with WTP>0*	$204
Emergency Automatic Braking			
Willingness to Pay to Add		*Present in a Vehicle**	
Do not want to pay anything	28.7%	Yes	5.4%
Less than $200	26.8%	*Interested in Technology*	
$200 to $299	18.3%	Not interested	22.8%
$300 to $399	13.7%	Slightly interested	31.5%
$400 and more	12.4%	Very interested	45.8%
Average WTP to Add	$183	*Average WTP of those with WTP>0*	$257
Level 3 Automation		***Self-parking Valet System***	
WTP to Add		*WTP to Add*	
Do not want to pay anything	55.4%	Do not want to pay anything	51.7%
Less than $2,000	13.3%	Less than $250	13.6%
$2,000 to $5,999	13.9%	$250 to $1,249	20.1%
$6,000 to $9,999	9.4%	$1,250 to $1,749	8.1%
$10,000 and more	7.9%	$1,750 and more	6.5%
Average WTP to Add	$2,438	*Average WTP to Add*	$436
Average WTP of those with WTP>0	$5,470	*Average WTP of those with WTP>0*	$902
Level 4 Automation		***Connectivity***	
WTP to Add		*WTP to Add*	
Do not want to pay anything	58.7%	Do not want to pay anything	39.1%
Less than $6,000	14.4%	Less than $75	20.3%
$6,000 to $13,999	10.3%	$75 to $124	16.5%
$14,000 to $25,999	9.3%	$125 to $174	11.6%
$26,000 and more	7.3%	$175 and more	12.5%
Average WTP to Add	$5,857	*Average WTP to Add*	$67
Average WTP of those with WTP>0	$14,196	*Average WTP of those with WTP>0*	$111

*Among the respondents who reported having at least one vehicle in their households.

Connectivity and Advanced Automation Technologies

It is evident that more than half of the respondents are not ready to pay for any of the advanced automation technology, but comparatively fewer (only around 39%) indicated $0 WTP to add connectivity. Among those who are willing to pay for advanced automation, the average WTP for Level 3 automation is $5,470 and for Level 4 automation, it is $14,196. Self-parking valet technology is valued at around $902 (with a simulation-projected price of $1,400 after 5 years, which may be too low [given how complex discerning a proper/legal parking spot can be in many settings]) and connectivity is valued at only $111 (projected price after five years is $140).

Opinions about CAV Technologies and Related Aspects

Some of the key opinion summaries are presented here. Most Americans perceive themselves as good drivers (88.2%), enjoy driving a car (75.7%), and tend to wait before adopting new technologies (79.3%). Around 54.4% of the respondents perceive AVs as a useful advancement in transportation, but 58.4% are scared of them. Only 19.5% of respondents will be comfortable sending an AV driving on its own (assuming that they as owners are liable for any accident it might cause), but 41.4% of the respondents agree with the statement that AVs will be omnipresent in the future. Around 49% of the respondents think that AVs will function reliably, while 44% believe the idea of AVs is not realistic.

It is interesting to note that more than half of the respondents (50.4%) are comfortable if their vehicle transmits information to other vehicles, and 42.9% are comfortable sending information to the vehicle manufacturer. The least proportions of the respondents were comfortable in sending information to insurance companies (36.4%) and toll operators (33.3%).

Most respondents are willing to trust technology companies (62.3%) and luxury vehicle manufacturers (49.5%) for production of well-designed AVs. Mass-market manufacturers come in third place, with support from 45.5% of the (population-weighted) respondents, and around 7.9% of the respondents do not trust any company to manufacture AVs.

Opinions about AV Usage by Trip Types and Long-distance Travel

Interestingly, around the same share of (population-corrected) respondents reported unwillingness to use AVs for short-distance (42.5%) or long-distance (40.0%) trips (under and over 50 miles, respectively). Around 40% reported a willingness to use AVs for their everyday trips, but just one-third plan to use them for their or their children's school trips. In the context of long-distance travel, the highest share of respondents (37.2%) plan to use AVs for trips with one-way distances between 100 and 500 miles. People also believe the number of long-distance trips they make will increase, by an average of 1.3 per month, after they have acquired an AV.

A FRAMEWORK TO FORECAST ADOPTION OF CAV TECHNOLOGIES

The simulation-based framework that forecasts the long-term adoption of CAV technologies consists of several stages, pursued together at a one-year time step. The first stage is a vehicle transaction and technology adoption model (as shown in Figure 1) that simulates the households' annual decisions to sell a vehicle ("sell"), buy vehicles ("buy"), sell a vehicle and buy vehicles ("replace"), add technology to the existing vehicles ("add technology"), and take no action ("do nothing"). A multinomial logit (MNL) model was estimated in BIOGEME (Bierlaire 2003) to determine the probabilities of making these decisions (see Table 3 for model specifications) and use these probabilities in the Monte Carlo method to ascertain the vehicle transaction and technology adoption choice of each household after each year.

In the case of a "sell" decision[6], the oldest vehicle (within a selling household) is disposed of. In the case of a "buy" decision, it is assumed that a household will buy (or lease) one or two

[6] It was assumed that the household sells or disposes only one vehicle at a time.

vehicles, and that each vehicle can be acquired new or used. It is important to determine whether a household purchases a new or used vehicle, since it was assumed that Level 3 and Level 4 automations cannot be retrofitted into used vehicles and that the cost of retrofitting existing vehicles with self-parking valet systems, Level 1 automation, and Level 2 automation are four times the cost of adding these technologies into a new vehicle (while it is being manufactured, essentially). Using the survey data (with population weights, to address sample biases), binary logit models were estimated to find the probabilities that a household acquiring a vehicle will purchase whether one or two vehicles and each vehicle will be whether new or used[7]. These probabilities were used in a Monte Carlo simulation (so that choices for each household in each year have random component, to reflect the uncertain nature of choice forecasting). Subsequently, DSRC-type connectivity is added to the purchased vehicle if a household's WTP for connectivity exceeds its price. If the purchased vehicle is used, then Level 1 and Level 2 automations are added based on the household's total budget for Level 2 technologies, and preferences and WTP for each Level 2 technology (or Level 1 technology, if only one technology is added to the vehicle). As mentioned earlier, respondents were also separately asked about WTP for a self-parking valet system[8], so this option is added to the used vehicle if the household's WTP exceeds that technology's price. If the purchased vehicle is new and the household's WTP for Level 4 automation exceeds the price of its addition, then Level 4 is added to the new vehicle. Otherwise a similar rule is checked for Level 3 automation. If the condition is met for Level 3, this automation is added to the new vehicle; otherwise, a self-parking valet system and Level 1 or Level 2 automation is added to the new vehicle with the same rules as described for the used-vehicle case.

In the case of a "replace" decision, a household is assumed to first choose a "sell" option, followed by a "buy" decision. In the case of an "add technology" decision, if an existing vehicle already has Level 3 or Level 4 automations, then no new technology is added to the vehicle. If this is not the case, then the existing technologies in the vehicle are excluded from the choice set, and a self-parking valet system (if not present in the existing vehicle) and Level 1 or Level 2 automation is added to the existing vehicle with the same rules as described for the used-vehicle case. In the "do nothing" case, all vehicles are retained and no technology is added. If a household does not own a vehicle, but the simulation suggests it choose "sell", "replace", or "add technology" options, the household is forced to pick the "do nothing" option. Finally, the population-weighted adoption rates of all technologies are extracted after each year.

This simulation framework does not consider changes in household demographics over time (other than the respondent's age and his/her household's overall vehicle ownership, since they are explanatory variables in the vehicle transaction and technology adoption model). Integrating household evolution models (as used in Musti and Kockelman [2011] and Paul et al. [2011]) may improve estimates of adoption rates and the nation's fleet evolution.

---

[7] These results are not included here, in order to meet TRB's word limit.

[8] A self-parking valet system was not characterized as a specific level of automation, but was assumed to be present in any vehicle having Level 3 or Level 4 automation.

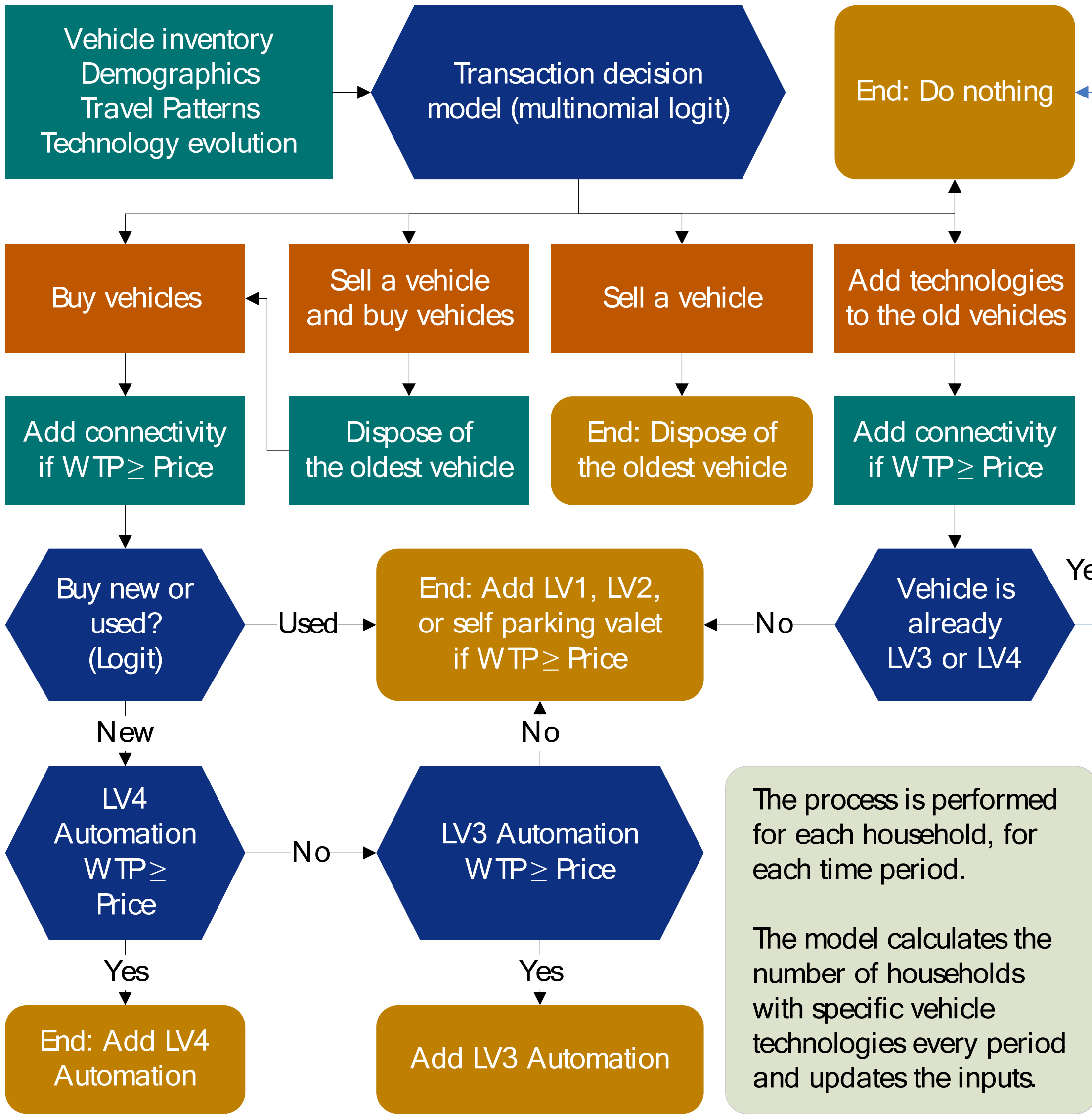

Figure 1: The Simulation-based Framework to Forecast Long-term Technology Adoption

VEHICLE TRANSACTION DECISIONS: MODEL SPECIFICATION

Table 2 summarizes key statistics for (population-weighted) person- and household-level variables, geocoded location variables, and transaction decision variables, as included in the vehicle transaction and technology adoption models.

Table 2: Population-weighted Summary Statistics of Explanatory Variables (N_{obs}=2,167)

Explanatory Variables	**Mean**	**SD**	**Min.**	**Max.**
Person Variables				
Age (years)	44.980	16.623	21	70
Male?	0.4897	0.5000	0	1
Single?	0.3358	0.4724	0	1

Explanatory Variables	**Mean**	**SD**	**Min.**	**Max.**
Bachelor's degree holder?	0.2561	0.4366	0	1
Full-time worker?	0.3146	0.4645	0	1
Have U.S. driver's license?	0.9045	0.2940	0	1
Disabled?	0.1285	0.3348	0	1
Annual vehicle-miles traveled over 9,000 miles?	0.3971	0.4894	0	1
Retired?	0.1848	0.3882	0	1
Drive alone for work trips?	0.5151	0.4999	0	1
Household Variables				
More than 3 members in the household?	0.2553	0.4361	0	1
Number of workers in the household	1.1944	0.9220	0	7
More than 1 worker in the household?	0.3491	0.4768	0	1
Household income	64,640	51,924	5,000	250,000
Age of the oldest vehicle in the household (in years)	10.661	7.3239	0	30
Number of vehicles owned by the household	1.7828	1.0176	0	6
At least one vehicle owned by the household?	0.9292	0.2566	0	1
Number of vehicles sold in the past 10 years	0.4230	0.6651	0	5
At least one vehicle sold in the past 10 years?	0.3488	0.4767	0	1
Location Variables				
% of families below poverty line in the census tract	12.301	10.155	0	77
Employed and over 16 years of age (per square mile)	2,826.0	6,232.6	1.1917	113,187
Population density (per square mile)	3,958.8	8,680.4	1.6496	132,409
Distance to transit stop (from home) exceeds 3 miles?	0.4868	0.4999	0	1
Distance to downtown (from home) exceeds 5 miles?	0.6428	0.4793	0	1
Response Variables	**Mean**	**SD**	**Min.**	**Max.**
Transaction Decisions				
Sell (a household vehicle in the coming year)	0.0382	0.1916	0	1
Replace a vehicle	0.2406	0.4276	0	1
Buy vehicles	0.1639	0.3703	0	1
Add technology to existing vehicles	0.0890	0.2848	0	1
Do nothing (maintain one's current vehicle holdings)	0.4683	0.4991	0	1
Buy Two Vehicles (in the coming year)?	0.0766	0.2659	0	1
Buy a New Vehicle (in the coming year)?	0.6495	0.4771	0	1

Table 3 shows the transaction model's final specification. The alternative specific constants (ASCs) indicate that, everything else being equal, households have inherent inclination and disinclination for "buy" and "replace" options, respectively. Specifically, older and single individuals with more than one worker in the household, who live farther from downtown in a lower-income neighborhood (all other attributes constant), are less likely to sell their vehicles in the coming year, while males in households with more vehicles appear more inclined to sell. Bachelor's degree holders, full-time workers, and younger, male respondents who drive alone for work, have more vehicles, and live in households with more than one worker are estimated to be more likely to replace a vehicle than others. Older and single (unmarried) respondents whose households own more vehicles appear to be less likely to buy a vehicle in the coming year. In contrast, respondents who drive alone to work, reside in households with more than one worker and more than three members, and have older vehicles appear more likely to buy a vehicle in the coming year. It is interesting to note that bachelor's degree holders who drive alone for work trips and live in neighborhoods with a higher density of employed individuals are more inclined toward the "add technology" option than "do nothing". However, all else equal, older individuals who have older vehicles are more likely to prefer the "do nothing" option over the "add technology" option.

Table 3: Transaction Decisions (Weighted Multinomial Logit Model Results)

Covariates	**Coef.**	**T-stat**
ASC_{Sell}	0	-fixed-
$ASC_{Replace}$	-1.810	-4.33
ASC_{Buy}	0.572	1.84
$ASC_{Add\ Technology}$	0	-fixed-
Sell		
Age (years)	-0.067	-10.15
Distance of downtown (from home) exceeds 5 miles?	-0.502	-2.06
Male?	0.686	2.64
Number of vehicles owned by the household	0.626	5.37
% of families below poverty line in the census tract	-0.020	-1.57
Single?	-0.884	-3.06
More than 1 worker in the household?	-0.833	-3.03
Replace		
Age (years)	-0.027	-6.29
Bachelor's degree holder?	0.556	4.93
Drive alone for work trips?	0.415	3.18
Full-time worker?	0.175	1.38
Male?	0.154	1.40
Number of vehicles owned by the household	0.127	1.84
At least one vehicle owned by the household?	1.440	3.65
Retired?	0.477	2.46
More than 1 worker in the household?	0.310	2.47
Buy		
Age (in years)	-0.039	-7.29
Drive alone for work trips?	0.172	1.30
More than 3 members in the household?	0.498	3.73
Age of the oldest vehicle in the household (in years)	0.016	1.73
Number of vehicles owned by the household	-0.283	-3.26
% of families below poverty line in the census tract	0.015	2.92
Retired?	0.265	1.22
Single?	-0.146	-1.03

Covariates	Coef.	T-stat
More than 1 worker in the household?	0.171	1.25
Add technology		
Age (in years)	-0.041	-10.52
Bachelor's degree holder?	0.382	2.34
Drive alone for work trips?	0.438	2.71
Age of the oldest vehicle in the household (in years)	-0.033	-2.88
Employed over 16 years (per square mile)	1.54E-05	2.11
Retired?	0.625	2.41
Fit statistics		
Null log-likelihood	-3487.65	
Final log-likelihood	-2688.66	
McFadden's R-square	0.229	
Adjusted R-square	0.220	
Number of observations	2,167	

Note: The "do nothing" option is the base alternative.

FORECASTED ADOPTION RATES OF CAV TECHNOLOGIES

Technology Pricing Scenarios

This simulation forecasts the annual adoption rates[9] of CAV technologies over the next 30 years (2016 to 2045) under eight different WTP, technology-pricing, and regulation scenarios (as shown in Table 4).

As indicated in Table 1, many respondents do not want to pay anything to add CAV technologies. For example, more than 50% respondents have $0 WTP to add Level 3 and Level 4 automations. Perhaps, these respondents are not able to conceive a world with only CAVs and also may have various safety and reliability concerns about the technology. As the public learns more about CAVs and more technological experiences start spilling into the public domain, these perceptions, and potential behavioral responses are apt to change, in some cases rapidly. In Scenario 1, original WTP (as reported by the respondents) was considered, and was assumed constant over the time. However, for all other scenarios (2 to 8), respondents who reported $0 WTP, were assigned a non-zero WTP[10] for year 2015, and WTP's temporal variation follows as per annual increment rates.

Scenarios 1 and 2 do not consider any NHTSA's current and probable technology adoption regulations, but remaining scenarios (3 to 8) assume mandatory adoption of ESC from year 2015 and connectivity from year 2020 on all new vehicles.

---

[9] Technology adoption rate means the percentage of the vehicles (population-weighted) having a specific technology. Vehicles with Level 3 and Level 4 automation are assumed to have all Level 2 automation technologies.

[10] To assign WTP to the respondents who do not want to pay anything for a specific technology, the sample was classified into 40 categories (based on household size, number of workers, and household vehicle ownership). Any respondent who does not want to pay anything for a specific technology was assigned a WTP of the 10th percentile value from all non-zeros WTP values in his/her household's category.

Table 4: WTP Rise, Technology-price Reduction, and Regulation Scenarios

Scenario	Annual Increase in WTP	Annual Technology Price Reduction Rate	Regulations
1	0%	10%	No
2	0%, but no zero WTP	10%	No
3	0%, but no zero WTP	5%	Yes
4	0%, but no zero WTP	10%	Yes
5	5%	5%	Yes
6	5%	10%	Yes
7	10%	5%	Yes
8	10%	10%	Yes

Note: In the "no zero WTP" scenarios, the tenth percentile WTP (among non-zero WTP individuals) for the individual's household-demographic cohort was used.

As mentioned earlier, it is difficult to estimate the price of a particular Level 1 or Level 2 technology, since automobile companies provide these technologies in packages. Thus, current prices for these technologies were estimated by analyzing packages provided by BMW, Mercedes, and other manufacturers. Prices to add connectivity, Level 3, and Level 4 automation were estimated based on experts' opinions. Table 5 shows an example of temporal variation of the prices to add CAV technologies to the new vehicles[11] for the annual price reduction rate of 5%.

Table 5: Technology Prices (in Year-2015 USD) Assuming 5% Annual Price Reduction Rates

Technology	2015	2020	2025	2030	2035	2040	2045
Electronic Stability Control	$100	$77.4	$59.9	$46.3	$35.8	$27.7	$21.5
Lane Centering	$950	$735.1	$568.8	$440.1	$340.6	$263.5	$203.9
Left-turn assist	$450	$348.2	$269.4	$208.5	$161.3	$124.8	$96.6
Cross Traffic Sensor	$550	$425.6	$329.3	$254.8	$197.2	$152.6	$118.1
Adaptive Headlights	$1,000	$773.8	$598.7	$463.3	$358.5	$277.4	$214.6
Pedestrian Detection	$450	$348.2	$269.4	$208.5	$161.3	$124.8	$96.6
Adaptive Cruise Control	$400	$309.5	$239.5	$185.3	$143.4	$111.0	$85.9
Blind-spot Monitoring	$400	$309.5	$239.5	$185.3	$143.4	$111.0	$85.9
Traffic Sign Recognition	$450	$348.2	$269.4	$208.5	$161.3	$124.8	$96.6
Emergency Automatic Braking	$450	$348.2	$269.4	$208.5	$161.3	$124.8	$96.6
Connectivity	$200	$154.8	$119.7	$92.7	$71.7	$55.5	$42.9
Self-parking Valet	$2,000	$1,548	$1,198	$926.6	$717.0	$554.8	$429.3
Level 3 Automation	$15,000	$11,607	$8,981	$6,949	$5,377	$4,161	$3,220
Level 4 Automation	$40,000	$30,951	$23,950	$18,532	$14,339	$11,096	$8,586

Comparison of Technology Adoption in Eight Scenarios

Tables 6 to 9 present the adoption rates every 5 years across all eight scenarios. Substantial differences are visible between the long-term adoption rates of all technologies (except Level 3

[11] In this study, costs for retrofitting self-parking valet system, Level 1, and Level 2 automations into the used vehicles are assumed four times of the cost for adding these technologies to the new vehicles.

and Level 4 automation)[12] in Scenarios 1 (constant WTP) and 2 (constant WTP, and all zero-WTP households replaced with low WTP value). For example, in 2045, the DSRC connectivity's adoption rate is estimated to be 59.5% in Scenario 1 and 83.5% in Scenario 2. Such differences emerge because many households cannot adopt some technologies in Scenario 1, even prices fall low, due to their initial, stated (and assumed-constant) zero WTP.

The regulations' (regarding adoption of ESC and connectivity) effects on CAV technologies' adoption rates can be observed by comparing the results of Scenario 2 (in Table 6) and Scenario 4 (in Table 7), since WTP and technology prices have the same temporal variations in both scenarios. In Scenario 2 (with no technology adoption regulations in place), ESC and connectivity options have adoption rates of 43.8% and 35.2% by 2025, and these numbers jump to 98.4% and 88.4% under Scenario 4, thanks to regulations.

The technology-pricing impacts on adoption of CAV technologies can be visualized by comparing adoption rates in Scenarios 3 and 4 (or 5 and 6, or 7 and 8), since these scenarios include regulations and have same temporal variations in WTP, but different technology-price variations. Table 7 shows that most of the technologies' long-term adoption rates under annual 10% technology-price reduction (Scenario 4) are much higher than that under 5% price-reduction (Scenario 3), since technologies are obviously affordable for many more households in Scenario 4 as compared to Scenario 3. For example, in 2045, Level 4 automation's adoption rates are 24.8% in Scenario 3 and 43.4% in Scenario 4.

The effect of WTP increments on CAV technologies' adoption rates can be observed by comparing the results of Scenarios 4, 6, and 8 (or 3, 5, and 7), since these scenarios have regulations, and same temporal variations of technology-pricing, but different WTP variations. As expected, Tables 7, 8, and 9, demonstrate that most of the technologies; long-term adoption rates in 0%, 5%, and 10% WTP increment scenarios are in increasing order. For example, in 2045, Level 4 automations' adoption rates in Scenarios 4, 6, and 8 are 43.4%, 70.7%, and 87.2%, respectively.

[12] In Scenario 2, all respondents with $0 WTP are assigned with non-zero WTP values, but new WTP values are not enough to make advanced automation technologies affordable, even at 10% price drop rates. Thus, Level 3 and Level 4 automations' adoption rates are not very different in Scenarios 1 and 2.

Table 6: Percentage of Vehicles with Technologies in Scenarios 1 and 2

Technology	**Scenario 1:** *Constant WTP, 10% drop in tech prices, and no regulation*							**Scenario 2:** *No-zero-WTP, 10% tech price drop, and no regulation*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	25.3	33.2	43.3	52.7	58.2	63.8	24.3	32.3	43.8	61.2	76.7	83.2	92.9
Lane Centering	4.4	8.3	18.9	31.0	40.8	48.8	56.8	4.4	8.6	20.2	33.5	45.9	55.2	68.8
Left-turn assist	3.8	9.9	20.1	32.4	41.8	50.3	58.1	3.8	10.4	21.8	35.1	47.2	65.6	80.2
Cross Traffic Sensor	10.9	12.9	22.6	35.1	45.1	52.6	60.3	10.9	13.8	25.9	41.1	53.7	66.0	82.8
Adaptive Headlights	10.2	9.7	18.8	30.9	41.0	49.2	58.0	10.2	9.8	19.8	32.4	46.2	55.9	77.5
Pedestrian Detection	3.7	10.6	21.7	34.5	44.1	52.6	59.8	3.7	11.2	24.1	38.2	50.3	69.1	82.8
Adaptive Cruise Control	13.3	14.9	24.1	35.2	44.7	52.2	59.8	13.3	16.2	27.0	40.1	53.4	62.2	76.1
Blind-spot Monitoring	11.7	15.0	26.1	38.5	48.2	55.1	62.1	11.7	17.3	31.9	46.3	59.7	67.8	80.7
Traffic Sign Recognition	2.0	7.7	18.0	30.0	39.8	48.9	57.0	2.0	7.6	18.4	31.4	43.5	63.3	78.6
Emergency Automatic Braking	5.6	11.8	24.4	37.1	46.9	54.6	61.6	5.6	11.8	26.4	43.7	57.7	74.3	86.2
Connectivity	0	17.7	34.8	44.7	51.1	53.0	59.5	0	18.0	35.2	46.1	57.6	61.4	83.5
Self-parking Valet	0	9.1	21.4	33.9	45.1	52.5	61.2	0	9.2	21.6	34.5	46.3	54.4	73.5
Level 3 Automation	0	2.1	4.6	7.6	8.3	8.0	10.4	0	3.0	5.3	7.7	8.7	7.9	13.7
Level 4 Automation	0	3.9	11.1	19.7	28.6	37.0	43.0	0	3.0	10.2	19.0	28.7	37.9	43.8

Table 7: Percentage of Vehicles with Technologies in Scenarios 3 and 4

Technology	**Scenario 3:** *No-zero-WTP, 5% drop in tech prices, and regulations*							**Scenario 4:** *No-zero-WTP, 10% drop in tech prices, and regulations*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	88.9	98.6	99.8	100	100	100	24.3	89.1	98.4	99.9	100	100	100
Lane Centering	4.4	6.1	12.0	19.7	27.1	33.1	40.7	4.4	8.5	19.9	33.0	45.5	53.9	66.5
Left-turn assist	3.8	7.9	14.2	21.3	28.1	35.1	42.5	3.8	10.0	21.8	35.0	46.5	60.6	75.1
Cross Traffic Sensor	10.9	11.7	16.8	22.9	31.9	39.1	47.4	10.9	13.7	25.4	39.8	52.2	62.2	76.8
Adaptive Headlights	10.2	7.6	11.2	18.3	26.4	32.6	39.9	10.2	9.5	19.6	32.3	46.1	53.6	71.6
Pedestrian Detection	3.7	8.3	15.0	23.2	30.7	38.3	45.5	3.7	10.7	24.0	37.5	49.7	63.4	77.1
Adaptive Cruise Control	13.3	13.2	18.4	25.7	33.2	39.2	46.5	13.3	16.5	28.1	39.7	53.0	60.4	73.4
Blind-spot Monitoring	11.7	13.8	20.3	29.7	39.6	45.7	53.5	11.7	16.5	31.6	45.6	59.1	66.0	77.2
Traffic Sign Recognition	2.0	5.4	10.5	17.7	24.9	31.4	38.1	2.0	7.3	18.2	30.9	42.7	58.7	73.9
Emergency Automatic Braking	5.6	8.6	15.6	26.1	34.7	43.4	51.2	5.6	12.3	26.3	42.3	57.2	69.1	80.9
Connectivity	0	36.5	88.2	98.4	99.7	100	100	0	41.3	88.4	98.4	99.7	100	100
Self-parking Valet	0	6.0	13.1	20.9	29.0	34.9	41.6	0	9.2	21.1	33.4	45.7	53.4	71.9
Level 3 Automation	0	1.9	3.2	4.5	6.5	8.1	8.9	0	2.7	5.1	7.5	8.7	8.2	13.9
Level 4 Automation	0	2.0	5.2	10.3	15.0	19.2	24.8	0	2.9	10.2	18.8	28.5	36.3	43.4

Table 8: Percentage of Vehicles with Technologies in Scenarios 5 and 6

Technology	**Scenario 5:** *5% rise in WTP, 5% drop in tech price, and regulations*							**Scenario 6:** *5% rise in WTP, 10% drop in tech price, and regulations*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	89.1	98.3	99.9	100	100	100	24.3	88.7	98.2	99.9	100	100	100
Lane Centering	4.4	8.5	21.1	33.5	43.5	53.1	59.8	4.4	10.3	26.8	44.5	56.5	81.4	92.9
Left-turn assist	3.8	10.3	22.0	35.0	44.4	59.2	71.5	3.8	11.9	27.8	44.8	66.2	88.1	96.3
Cross Traffic Sensor	10.9	14.3	25.7	39.6	50.6	60.9	73.4	10.9	15.7	32.1	50.2	68.9	87.3	96.3
Adaptive Headlights	10.2	10.0	20.5	32.3	43.4	53.0	67.1	10.2	11.0	26.4	44.5	63.4	84.8	95.4
Pedestrian Detection	3.7	11.1	24.5	38.1	47.9	61.4	74.0	3.7	13.2	30.9	48.5	68.6	88.6	96.5
Adaptive Cruise Control	13.3	16.1	27.4	39.4	51.8	60.3	68.3	13.3	18.3	33.9	51.5	66.7	86.4	95.8
Blind-spot Monitoring	11.7	17.5	30.8	44.6	57.5	66.3	73.6	11.7	17.8	37.7	57.3	71.6	88.4	96.3
Traffic Sign Recognition	2.0	7.1	19.0	30.7	41.4	56.5	70.0	2.0	8.6	24.5	41.0	63.8	87.3	96.2
Emergency Automatic Braking	5.6	11.6	26.4	42.4	54.6	67.3	77.8	5.6	14.1	34.2	55.0	73.3	91.0	97.2
Connectivity	0	39.1	89.3	98.5	99.8	100	100	0	40.5	88.8	98.2	99.7	100	100
Self-parking Valet	0	8.6	21.8	34.0	44.4	52.4	67.1	0	10.2	26.9	44.2	64.5	85.6	96.5
Level 3 Automation	0	2.3	5.3	8.1	8.5	8.3	8.2	0	2.1	6.1	8.4	8.5	28.6	16.3
Level 4 Automation	0	3.3	10.8	19.0	27.2	35.9	43.2	0	4.7	15.1	27.2	38.3	45.7	70.7

Table 9: Percentage of Vehicles with Technologies in Scenarios 7 and 8

Technology	**Scenario 7:** *10% rise in WTP, 5% drop in tech price, and regulations*							**Scenario 8:** *10% rise in WTP, 10% drop in tech price, and regulations*						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Electronic Stability Control	24.3	89.7	98.1	99.8	100	100	100	24.3	89.1	98.8	99.9	100	100	100
Lane Centering	4.4	10.8	25.5	42.1	55.1	78.1	90.3	4.4	13.5	32.8	51.2	79.0	94.0	97.9
Left-turn assist	3.8	11.6	26.5	43.0	65.1	83.6	95.0	3.8	14.1	34.1	60.9	87.3	96.4	98.4
Cross Traffic Sensor	10.9	15.6	30.8	48.3	65.4	84.6	95.0	10.9	18.2	39.3	63.6	87.0	96.6	98.5
Adaptive Headlights	10.2	11.4	25.0	42.3	58.5	81.3	92.5	10.2	13.4	32.8	55.8	81.4	95.5	98.2
Pedestrian Detection	3.7	12.9	28.8	45.8	67.9	84.6	95.3	3.7	15.3	37.6	63.7	87.9	96.8	98.7
Adaptive Cruise Control	13.3	18.0	31.7	49.1	62.5	82.8	92.8	13.3	20.3	40.4	60.2	83.2	95.4	98.2
Blind-spot Monitoring	11.7	18.5	35.6	54.6	67.7	85.4	94.0	11.7	20.5	45.5	66.4	85.9	96.3	98.6
Traffic Sign Recognition	2.0	9.0	23.2	39.0	62.0	82.6	94.9	2.0	10.9	30.0	57.9	86.4	96.4	98.4
Emergency Automatic Braking	5.6	13.9	32.9	52.1	72.4	88.0	96.4	5.6	16.6	41.5	68.4	90.0	97.3	98.9
Connectivity	0	41.8	89.1	98.3	99.7	100	100	0	41.3	89.4	99.0	99.9	100.0	100.0
Self-parking Valet	0	10.5	25.5	41.6	57.6	82.4	92.9	0	12.6	32.9	54.6	80.3	96.0	99.4
Level 3 Automation	0	2.5	5.9	8.3	8.2	26.5	25.5	0	3.5	6.0	7.7	27.7	11.6	2.9
Level 4 Automation	0	4.7	13.8	25.5	36.4	44.3	59.7	0	5.5	19.4	33.8	44.2	74.7	87.2

Adoption Rates of Connectivity and Level 2 Technologies

It is interesting to note that around 98% of vehicle-fleet is likely to have ESC and connectivity in year 2025 and 2030, respectively, under NHTSA's current and probable regulations (Scenarios 3 to 8). However, it is worth noting that in case of no regulations, even at 10% annual drop in technology prices and no-zero, but constant WTP (Scenario 2), 92.9% of vehicles would have ESC and 83.5% would have connectivity in 2045 (see Table 6). Thanks to NHTSA's regulations, which are likely to diminish more than 15 to 20 years of gap in adoption of these technologies, and make U.S. roads safer.

In Scenario 6 (5% rise in WTP and 10% drop in technology prices), Scenario 7 (10% rise in WTP and 5% drop in technology prices), and Scenario 8 (10% rise in WTP and 10% drop in technology prices), all Level 1 technologies are estimated to have more than 90% adoption rates in 2045. Level 1 technologies' adoption rates are further explored in Scenario 3 (5% drop in technology prices and constant, but no-zero WTP) and Scenario 5 (5% rise in WTP and 5% drop in technology prices). Traffic sign recognition is the least adopted and least interesting Level 1 technology in 2015, and is anticipated to remain least adopted, with adoption rates of 38.1% in 2045 in Scenario 3, but fourth least adopted (out of 9, excluding ESC), with adoption rates of 70% in Scenario 5[13]. The opinion summaries suggest that blind-spot monitoring and emergency automatic braking are the two most interesting Level 1 technologies for Americans; and these are anticipated to be the most and second-most adopted Level 1 technologies (excluding ESC) in 2045 in Scenario 3, with adoption rates of 53.5% and 51.2%; however these are third-most and most adopted Level 1 technologies in Scenario 5, with adoption rates of 73.6% and 77.8%. Pedestrian detection is the second-least adopted technology in 2015, but is expected to be the second-most adopted Level 1 technology (out of 9, excluding ESC) in 2045 in Scenario 5, with adoption rate of 74.0%.

Adoption Rates of Advanced Automation Technologies

It is interesting to note that as WTP-rise and technology price-drop rates increase, Level 4 automations' adoption rates shoot up and at the same time, Level 3 automations' adoption rates drop down. For example, in 2045, Level 3 and Level 4 adoption rates are forecasted to be 8.2% and 43.2% in Scenario 5 (5% drop in technology prices and 5% WTP rise), which change to 2.9% and 87.2% in Scenario 8 (10% drop in technology prices and 10% WTP rise). This is happening because the simulation framework first checks whether a new-vehicle-buyer household can afford Level 4 automation (WTP ≥ price of technology) in that specific year or not and if yes, then Level 4 automation is added to the new vehicle, else same rule is checked for Level 3. So, with the increase in WTP or/and reduction in technology prices, many households are able to afford Level 4 and thus, due to this hierarchical framework, Level 3 automation is automatically skipped from their choice sets. Self-parking valet system is likely to be adopted by 34.0% to 54.6% of vehicle fleet in 2030 and 67.1% to 99.4% of vehicle-fleet in 2045[14].

CONCLUSIONS

---

13 Lane centering is the least adopted Level 1 technology in Scenario 5 in 2045, with adoption rate of 59.8%.

14 The lower bounds on adoption rate comes from a 5% drop in technology prices and 5% WTP rise and upper bound is forecasted via a 10% drop in technology prices and 10% increase in WTP values.

These survey results offer insights about Americans' current adoption of, WTP for, and interest in CAV technologies, while helping traffic engineers, planners and policymakers forecast long-term (year 2015 to 2045) adoption of these technologies under eight-different technology price (5% and 10% annual reduction rates), WTP (0%, 5% and 10% annual increment rate), and regulations (on ESC and connectivity) scenarios.

Fleet evolution results indicate that around 98% of U.S.'s vehicle-fleet is likely to have ESC and connectivity in year 2025 and 2030, respectively, under NHTSA's current and probable regulations. Thanks to these regulations, which are likely to diminish more than 15 to 20 years of gap in adoption of these technologies, and make U.S. roads safer. In all scenarios with at least 10% WTP increment rate or at least 10% price reduction rate, all Level 1 technologies are estimated to have more than 90% adoption rates in 2045. More than half of the respondents are not willing to pay anything to add the advanced automation technologies (self-parking valet, and Level 3 and Level 4 automations). Thus, the population-weighted average WTP to add these technologies is less than half of the average WTP of the respondents who have non-zero WTP for these technologies. Average WTP (of the respondents with a non-zero WTP) to add connectivity and Level 3 and Level 4 automations are $110, $5,551, and $14,589, respectively. Long-term fleet evolution suggests that Level 4 AVs are likely to be adopted by 24.8% to 87.2% of vehicle fleet in 2045[15].

These results reflect the current perceptions of Americans. As the public learns more about CAVs and more technological experiences start spilling into the public domain, these perceptions, and potential behavioral responses are apt to change. For example, a large proportion (more than 50%) of individuals who do not want to pay anything for advanced automation technologies may change their perspectives, as the technology becomes proven and they see their neighbors, friends and co-workers adopt AVs to great success. Alternatively, a well-publicized catastrophe (such as a multi-vehicle, multi-fatality cyber-attack) could set adoption rates back years.

WTP is typically a function of demographics and built-environment factors and thus is expected to change over the years. Since this study does not consider the evolution of a household's demographic and built-environment characteristics (e.g., change in household size and neighborhood population density), household's WTP over time is considered to increase at constant annual rates. However, integration of household evolution over the years, followed by behaviorally-defensible temporal variation in the households' WTP, can change the estimates of the technology adoption rates. This is a potential future research direction. Lastly, SAVs are likely to change future vehicle ownership patterns (Fagnant et al. 2015) and thus, inclusion of them in the simulation framework can be a good extension of this study.

ACKNOWLEDGEMENTS

The authors are thankful to the Texas Department of Transportation (TxDOT) for financially supporting this research. The authors thank Dr. Duncan Stewart, Paul Avery, Dr. Dan Fagnant, Lisa Loftus-Otway, Kevin Pappas, and Maureen Kelly for their constructive comments and

[15] The lower-bound on adoption rate comes from a 5% drop in technology prices and constant WTP, and the upper bound is forecasted via a 10% drop in technology prices and 10% increase in WTP values.

editing. They are also obliged to Gleb Domnenko for help in data cleaning and calculating summary statistics.

REFERENCES

Automotive Digest (2014) NHTSA calls for V2V technology in models built after 2020. Retrieved from: http://automotivedigest.com/2014/08/nhtsa-eyes-half-million-crashes-prevented-v2v-technology/ (July 19, 2015).

Alexander, D., and Gartner, J. (2014) Self-driving vehicles, advanced driver assistance systems, and autonomous driving features: Global market analysis and forecasts. Navigant Consulting, Inc. Retrieved from: https://www.navigantresearch.com/research/autonomous-vehicles (June 21, 2015).

Bansal, P., Kockelman,K., and Singh, A. (2015) Assessing public opinions of and interest in new vehicle technologies: an Austin perspective. Under review for publication in *Transportation Research Part C*. Retrieved from: http://www.caee.utexas.edu/prof/kockelman/public_html/TRB16NewTechsAustin.pdf (July 22, 2015).

Bierlaire, M. (2003) BIOGEME: A free package for the estimation of discrete choice models. *Proceedings of the 3rd Swiss Transportation Research Conference*, Ascona, Switzerland.

Citi GPS: Global Perspectives & Solutions. (2014) The car of the future: Transforming mobility as we know it. Retrieved from: https://www.citivelocity.com/citigps/ReportSeries.action?recordId=27 (June 28, 2014).

Fagnant, D. J., Kockelman, K., and Bansal, P. (2015) Operations of a shared autonomous vehicle fleet for the Austin, Texas market. Proceedings of the 94th Annual Meeting of the Transportation Research Board (No. 15-1958) and forthcoming in *Transportation Research Record.*

Fagnant, D. J., and Kockelman, K. (2015) Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, 77: 167-181.

Harrop, P., and Das, R. (2015) Autonomous Vehicles: Land, Water, Air 2015-2035. Retrieved from: http://www.prnewswire.com/news-releases/autonomous-vehicles-land-water-air-2015-2035-300096548.html (June 28, 2014).

Hars, A. (2014) Autonomous vehicle roadmap: 2015-2030. Driverless Future website. Retrieved from: http://www.driverless-future.com/?p=678 (June 29, 2015).

IHS Automotive. (2014) Emerging technologies: Autonomous cars—not if, but when. Retrieved from: http://collision.honda.com/ihs-automotive-forecasts-54-million-self-driving-cars-used-globally-by-2035-#.VbVnkPlViko (July 15, 2015).

Laslau, C., Holman, M., Saenko, M., See, K., and Zhang, Z. (2014) Set autopilot for profits: Capitalizing on the $87 billion self-driving car opportunity. Retrieved from: http://www.giiresearch.com/report/lux301508-set-autopilot-profits-capitalizing-on-87-billion.html (July 22, 2015).

Litman, T. (2015) Autonomous vehicle implementation predictions. Victoria Transport Policy Institute. Retrieved from: http://www.vtpi.org/avip.pdf (March 10, 2015)

Mosquet, X., Dauner, T., Lang, N., Rüßmann, M., Mei-Pochtler, A., Agrawal, R., and Schmieg, F. (2015) Revolution in the driver's seat: The road to autonomous vehicles. Retrieved form: https://www.bcgperspectives.com/content/articles/automotive-consumer-insight-revolution-drivers-seat-road-autonomous-vehicles/ (July 15, 2015).

Musti, S., and Kockelman, K. (2011) Evolution of the Household Vehicle Fleet: Anticipating Fleet Composition and PHEV Adoption in Austin, Texas. *Transportation Research Part A* 45 (8): 707-720.

NHTSA (National Highway Traffic Safety Administration) (2012) New NHTSA report shows Federal ESC requirement saving lives. Press release NHTSA 33-12. Retrieved from: http://www.nhtsa.gov/About+NHTSA/Press+Releases/2012/New+NHTSA+Report+Shows+Federal+ESC+Requirement+Saving+Lives (July 19, 2015).

NHTSA (National Highway Traffic Safety Administration) (2013) Preliminary statement of policy concerning automated vehicles. Washington, D.C. Retrieved from: http://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf (October 15, 2014).

Paul, B., Kockelman, K., Musti, S. (2011) Evolution of the Light-Duty-Vehicle Fleet: Anticipating Adoption of Plug-In Hybrid Electric Vehicles and Greenhouse Gas Emissions Across the U.S. Fleet. *Transportation Research Record* No. 2252: 107-117.

PUMS (Public Use Microdata Sample) (2013) United State Census Bureau: American Community Survey. Retrieved from: http://www.census.gov/acs/www/data_documentation/pums_data (October 15, 2014).

Rowe, R. (2015, 07 19). Self-Driving Cars, Timeline. Retrieved from: http://www.topspeed.com/cars/car-news/self-driving-cars-timeline-ar169802.html (July 20, 2015).

Schoettle, B., and Sivak, M. (2014) A survey of public opinion about autonomous and self-driving vehicles in the US, the UK, and Australia. University of Michigan, Technical Report No. UMTRI-2014-21. Retrieved from: http://deepblue.lib.umich.edu/bitstream/handle/2027.42/108384/103024.pdf?sequence=1&isAllowed=y (October 15, 2014).